

Detection of an X-Ray Hot Region in the Virgo Cluster of Galaxies with *ASCA*

K. Kikuchi¹, C. Itoh², A. Kushino², T. Furusho², K. Matsushita², N. Y. Yamasaki², T. Ohashi², Y.
Fukazawa³, Y. Ikebe⁴, H. Böhringer⁴, and H. Matsumoto⁵

Received _____; accepted _____

¹Space Utilization Research Program, National Space Development Agency of Japan, 2-1-1 Sengen, Tsukuba, Ibaraki 305-8505, Japan; Kikuchi.Kenichi@nasda.go.jp

²Department of Physics, Tokyo Metropolitan University, 1-1 Minamiosawa, Hachioji, Tokyo 192-0397, Japan

³Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

⁴Max-Planck-Institut für extraterrestrische Physik, Postfach 1603, D-85740, Garching, Germany

⁵Center for Space Research NE80-6045, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA02139-4307, USA

ABSTRACT

Based on mapping observations with *ASCA*, an unusual hot region with a spatial extent of 1 square degree was discovered between M87 and M49 at a center coordinate of R. A. = 12h 27m 36s and Dec. = $9^{\circ}18'$ (J2000). The X-ray emission from the region has a $2 - 10$ keV flux of 1×10^{-11} ergs s $^{-1}$ cm $^{-2}$ and a temperature of $kT \gtrsim 4$ keV, which is significantly higher than that in the surrounding medium of ~ 2 keV. The internal thermal energy in the hot region is estimated to be $VnkT \sim 10^{60}$ ergs with a gas density of $\sim 10^{-4}$ cm $^{-3}$. A power-law spectrum with a photon index $1.7 - 2.3$ is also allowed by the data. The hot region suggests there is an energy input due to a shock which is probably caused by the motion of the gas associated with M49, infalling toward the M87 cluster with a velocity $\gtrsim 1000$ km s $^{-1}$.

Subject headings: galaxies: clusters: individual (Virgo) — galaxies: intergalactic medium — X-rays: galaxies

1. Introduction

Recent X-ray observations are revealing significant large-scale variations of temperature and surface brightness in many clusters, providing evidence that clusters are evolving. Hydrodynamic simulations show that clusters recently formed through mergers should indicate a complex temperature structure, and become more regular with time (e.g. Roettiger, Burns, & Loken 1993; Takizawa 1999). Thus, spatial distributions of the temperature of the intracluster medium (ICM) provide important clues about the dynamical evolution and the present state of the cluster.

In this letter, we perform a detailed investigation on the temperature structure of the ICM in the Virgo cluster, based on extensive mapping observations with *ASCA* (Tanaka, Inoue, & Holt 1994). This nearest rich cluster enables *ASCA* to perform spatially resolved spectroscopy with moderate spatial resolution, and hot-gas properties can be studied in both galaxy scales (< 100 kpc) and in the whole cluster scale (> 1 Mpc). The Virgo cluster is thought to be a dynamically young system as recognized from its irregular structure in the optical and X-ray bands. Thus, the present mapping study of the cluster should provide us with valuable information to investigate the on-going heating process in the ICM.

We assume the distance to the Virgo cluster to be 20 Mpc (e.g. Federspiel et al. 1998), hence $1'$ angular separation at the cluster corresponds to 5.8 kpc. The solar number abundance of Fe relative to H is taken as 4.68×10^{-5} (Anders & Grevesse 1989) throughout this letter.

2. Observation and Analysis

2.1. Observation

The mapping observations of the Virgo cluster have been carried out in December 1996 to December 1998, with 28 pointings and a total exposure time of ~ 500 ksec (Matsumoto et al. 1999; Ohashi et al. 1999; Yamasaki et al. 1999). Together with the data in the archive, the area covered with *ASCA* in the Virgo cluster is ~ 10 deg². Figure 1 shows the *ASCA* observed regions overlayed on the X-ray contours with *ROSAT* (Böhringer et al. 1994). The radius of the circles is $22'$ corresponding to GIS field of view (Makishima et al. 1996; Ohashi et al. 1996).

We selected the GIS data observed with the telescope elevation angle from the Earth rim $> 5^\circ$, and the data taken with unstable attitude after maneuvers were discarded. Flare-like events due to the background

fluctuation were also excluded (Ishisaki 1996). The cosmic X-ray background (CXB) was estimated from the archival data taken during 1993–1994 (Ikebe 1995), and the long-term variability of the non X-ray background of the GIS (Ishisaki 1996) was corrected for.

2.2. Image Analysis

To derive the pure ICM component, contaminating X-ray sources have to be excluded. We carried out a source detection analysis developed for the CXB study by Ueda (Ueda et al. 1999), who dealt with the complicated detector response in a systematic way including the position- and energy-dependence of the point spread function (PSF) of the *ASCA* X-ray telescope. Pointings containing bright sources such as M87, M49, A1553, and A1541 were excluded from the analysis, leaving 29 pointings to be analyzed (indicated by blue circles in Figure 1). We adopt a rather low flux level in detecting the source candidates, 3σ above the background in 0.7 – 7 keV band, since our interest is in the remaining diffuse component. The analysis detected 231 source candidates with X-ray flux $\gtrsim 1 \times 10^{-13}$ erg cm $^{-2}$ s $^{-1}$ in the 2 – 10 keV band and all of them have been masked out from the mapping data (see Figure 1). The mask regions centered on the candidate positions have radii depending on the source flux, since brighter sources affect wider regions due to the image spread by the PSF effect. The mask radius is determined where the surface brightness due to the source drops to less than 5% of the ICM level.

To examine spatially resolved spectral features, we need to know the surface brightness distribution in the whole cluster to estimate the amount of the stray light, which consists of photons generated outside the field of view (e.g. Honda et al. 1996). Fortunately, the RASS (*ROSAT* All-Sky Survey, Böhringer et al. 1994; Voges et al. 1996) data is available for this purpose, and we can produce the template of the brightness profile. In the RASS image, diffuse soft X-ray emission, which possibly comes from the rim of LOOP I (e.g. Raymond 1984; Egger & Aschenbach 1995), is present in the direction of the Virgo cluster (Snowden et al. 1995). Therefore, we use the PSPC data only above 0.9 keV to exclude possible soft X-ray contamination. Spatially uniform background, obtained from a blank sky region, was subtracted from the Virgo RASS data. Based on this template image, a ray-tracing simulation (Tsusaka et al. 1995) for the GIS observation was carried out assuming a uniform temperature of 2.0 keV and a metallicity of 0.2 solar, which are the typical parameters in the Virgo field (e.g. Koyama, Takano, & Tawara 1991; Matsumoto et al. 1999).

As a result, we found that the intermediate region between M87 and M49 was almost free from stray light from M87 and M49. The contaminating flux from these 2 galaxies is less than a few %. Considering

the complex spectral structures (such as temperature and abundance gradients) in these galaxies, this makes the data analysis for the intermediate region much easier.

2.3. Spectral Analysis

To derive spectral parameters (such as temperature and surface brightness) in a region, we have to know parameters in the surrounding regions to evaluate the contamination of stray light. We carried out a first-order estimation of the spectral parameters, adopting an analysis method developed by Honda et al. (1996). This is performed by fitting individual spectra with a modified response functions that partly compensates the effect of the stray light. The RASS image obtained in the previous section is used to estimate the amount of the stray light.

A spectral analysis has been performed for each pointed region in the 0.7 – 8 keV band with a Raymond-Smith model (Raymond & Smith 1977, hereafter R-S model). The interstellar absorption N_{H} is fixed to the Galactic value ($1.7 - 2.5 \times 10^{20} \text{ cm}^{-2}$). The temperature distribution derived from the GIS spectral fits is shown in Figure 2, with a color-coded plot of temperature in the left panel and a plot as a function of distance from M87 in the right panel, respectively.

As shown in Figure 2, the temperature around M87 is ~ 2.5 keV and slightly decreases to ~ 2.0 keV at $\sim 1^\circ$ away from M87 in the northwest region. In the south region, the average temperature at a distance of 2° from M87 is still ~ 2.5 keV, with a large scatter from 1.8 keV to 3.4 keV. The metal abundance is poorly constrained in most of the regions because of low photon statistics. We only mention that the best-fit values suggest that the metal abundance in the general cluster regions is around 0.2 solar with a scatter of about ± 0.2 solar from position to position. If we fitted the spectra with free absorption, the data generally require that no absorption (even the Galactic N_{H}) is present. This suggests existence of an additional soft component below ~ 1 keV, which may be the foreground emission of the Galactic soft X-rays.

3. The Hot Region

As shown in Figure 2, three regions W1, W2 and W3 along the “emission bridge” between M87 and M49 show the ICM temperatures rising to ~ 3 keV. To improve the statistics, the three spectra are combined (hereafter called W123) because individual fits indicate statistically the same temperature. For comparison, the spectra for regions E1, E2, and E3 (hereafter E123), just to the east of W123, are also

combined. Both W123 and E123 regions are elongated in parallel to the “emission bridge”, and the distance from M87 and M49 is almost the same. Errors in the contaminating spectra from nearby bright sources (i.e. A1553, NGC 4325, A1541, and QSO 1225+089) and those in the remaining fluxes of masked-out sources are the major origin of the systematic error for temperatures in W123 and E123. This error is found to be less than 0.2 keV, and its effect works on the two temperatures in the same sense: thus keeping the temperature difference the same.

The single-temperature model gives a poor fit in the energy range 0.7 – 8.0 keV for the 2 spectra W123 and E123. As shown in Table 1, the best-fit results are $\chi^2/\nu = 45.2/21$ and $31.1/21$ for W123 and E123, respectively. This is mainly due to excess emission below 1 keV in both spectra. A two-component (R-S and a soft thermal bremsstrahlung) model improves the fit to $\chi^2/\nu = 21.8/20$ and $\chi^2/\nu = 27.2/20$ for W123 and E123, respectively (see Figure 3). The additional thermal bremsstrahlung component yields the best-fit temperature $kT = 0.2 - 0.3$ keV with $F_X \sim 0.8 \times 10^{-15}$ erg cm $^{-2}$ s $^{-1}$ arcmin $^{-2}$ for 0.5 – 2 keV for both W123 and E123 spectra. These values are close to the ROSAT result ($kT = 0.15$ keV and $F_X = 0.6 \times 10^{-15}$ ergs cm $^{-2}$ s $^{-1}$ arcmin $^{-2}$ in 0.5 – 2 keV band, Irwin & Sarazin (1996)), supporting the view that the soft emission is due to the Galactic hot interstellar medium. These results indicate that the region W123 has a significantly high temperature of ~ 4 keV, while E123, just in the east of W123, shows ~ 2 keV which is the typical temperature of the Virgo cluster.

Based on these results, we neglect the energy range below 2 keV and look into the pure ICM component in the region W123. We also subtracted contaminating photons, which come from the surrounding region of W123, assuming the temperature and metallicity of the surrounding ICM are 2 keV and 0.2 solar, respectively. Fixing the abundance to 0.2 solar, acceptable fits with R-S model are obtained with $\chi^2/\nu = 10.5/11$ (Table 1). The ray-tracing simulation gives a systematic error for the stray-light intensity by $-30\% - +10\%$ as estimated from offset observations of the Crab nebula (Ishisaki 1996). The systematic error due to a fluctuation of the CXB flux is $\sim 10\%$ for the GIS field of view, and the uncertainty in the estimation of the non X-ray background level is 6%. Including all these errors, we can conclude that the temperature in W123 is still higher than that in E123 with more than 90% confidence. The total flux of the hot region in 2 – 10 keV band is $(9.2 - 10.3) \times 10^{-12}$ erg cm $^{-2}$ s $^{-1}$ at the 90% confidence limit, and the emission measure $\int n^2 dl$ is estimated to be $(3.4 - 5.0) \times 10^{16}$ cm $^{-5}$ assuming an extent of the hot region to be 4×10^3 arcmin 2 .

So far, the “hot” emission has been assumed to have a thermal spectrum. However, the data also allow non-thermal (power-law) models. Spectral fit for the 2 – 8 keV hot region data (W123) with a power-law

model gives an acceptable result of $\chi^2/\nu = 9.9/11$ with a photon index between $1.7 - 2.3$ at the 90% confidence (see Table 1). Since no significant Fe-K line is seen in the W123 spectrum with $EW \leq 821$ eV for a 6.7 keV line at the 90% confidence, the diffuse non-thermal emission remains as a possibility from the ASCA observations.

4. Discussion

The previous *Ginga* observations have suggested a temperature rise in the ICM from M87 to M49 (Takano 1990; Koyama, Takano, & Tawara 1991). However, *ROSAT* data showed no such evidence (Böhringer et al. 1994) and implied a possibility that the non-imaging *Ginga* data were contaminated by background sources. The extensive mapping observations from *ASCA* have shown the correct temperature structure in the Virgo cluster for the first time and unambiguously detected an unusual “hot” region in the ICM. This detection provides a clear evidence that the Virgo cluster is a young system in which a local gas heating is taking place now in the cluster outskirts.

The emission measure of the hot region W123 obtained in the previous section gives a rough estimate of the gas density n to be of the order of $1 \times 10^{-4} \text{ cm}^{-3}$. Here, we assume that the line-of-sight depth of the hot component is ~ 300 kpc which is the same order as the projected length of the region. The internal thermal energy of the hot component, $E_{\text{th}} = VnkT$ where V and T are volume and temperature, is calculated as $\sim 10^{60}$ ergs. This level of energy is orders of magnitude lower than the kinetic energy involved in a typical subcluster merger (10^{63-64} ergs). This means that if there is a bulk motion of gas in this region with $v \approx 1000 \text{ km s}^{-1}$, caused by an infall of galaxies or a small group of galaxies, then it can supply enough energy to heat up the gas to the observed temperature.

One might feel some difficulty to heat up a localized spot by a merger, however, such a local effect could be produced by the merging of a subclump of the irregular M49 subcluster. Time scale for thermal conduction is roughly estimated as $t_{\text{cond}} \approx 8 \times 10^8 \text{ yr}$ for the gas density in the hot region and the scale length of the temperature gradient to be 500 kpc. If the gas moving with $v \approx 1000 \text{ km s}^{-1}$ receives some heat input, the hot region would become elongated by ~ 800 kpc because of the slow heat conduction. This situation could be related with the observed north-south elongation of the hot region.

Honda et al. (1996) reported temperature variation of the ICM in the Coma cluster, and found a remarkable hot region ($\gtrsim 11$ keV) which is distinct from the average temperature of the whole cluster (~ 8 keV). This hot region is located at $40'$ (1.6 Mpc) offset from the cluster center, and has an angular extent

of $\sim 20'$ radius. We can roughly estimate the extra internal energy in the Coma hot region as $\sim 8 \times 10^{61}$ ergs, which is nearly 2 orders of magnitude higher than that in the Virgo case.

Irwin & Sarazin (1996) discuss that M49 is moving supersonically ($v \approx 1300 \text{ km s}^{-1}$) in the Virgo ICM toward the direction of M87. The gravitational mass of M49 subcluster is estimated as $8.7 \times 10^{13} M_{\odot}$ from the *ROSAT* observation (Schindler, Binggeli, & Böhringer 1999). Then the kinetic energy of the M49 subcluster is roughly estimated as 1×10^{63} ergs, which is sufficiently large to heat up the hot-region gas. Using Rankine-Hugoniot jump condition (e.g. Shu 1992), the Mach number of the shock wave to heat up 2 keV gas to ~ 4 keV should be ~ 2 . Since the sound velocity of the 2 keV gas is $\sim 700 \text{ km s}^{-1}$, the required velocity is close to the Irwin & Sarazin result.

Hard X-ray ($kT \gtrsim 10 \text{ keV}$) emission from clusters of galaxies was reported from previous observations (e.g. Fusco-Femiano et al. 1999 for Coma cluster), and the existence of non-thermal emission has been suggested. For the hot region detected here, we cannot confirm whether the origin of the hard emission is thermal or non-thermal, because of the lack of observational evidences. If we assume that relativistic electrons are produced by first-order Fermi acceleration, the momentum spectrum of the electrons is described as $N(p) = N_0 p^{-\mu}$. Here, $\mu = (r + 2)/(r - 1)$ and r is a ratio of the shock compression. For the shock with a Mach number ~ 2 , the exponent is implied as $\mu \approx 3.3$. In such a steep spectra, an energy loss due to nonthermal bremsstrahlung dominates the inverse Compton loss (Sarazin & Kempner 1999). The electrons lose their energy through Coulomb loss, whose time scale is estimated as $t_{\text{Coul}} \approx 3 \times 10^8 \gamma \text{ yr}$. This is similar to the t_{cond} estimated above.

Above considerations suggest that in both thermal and non-thermal cases, the extra energy built up in the hot region would dissipate away within about 1 Gyr, due to thermal conduction or Coulomb loss. Therefore, it seems likely that the energy supply into the hot region has started only within the past 1 Gyr, or alternatively a long continuous supply of energy has been occurring here over a cosmological time scale. The infall of the M49 subcluster can supply energy into ICM for a very long time and is probably connected with the local gas heating as detected in the Virgo cluster.

We thank Y. Ueda and Y. Ishisaki for their support of source detection analysis and background estimation. Stimulating discussion with T. Reiprich, C. Sarazin, K. Masai, S. Okamura and M. Takizawa are also acknowledged. K. K. acknowledges hospitality in MPE and support from the Japan Science and Technology Corporation (JST). This work is partly supported by the Grants-in Aid of the Ministry of Education, Science, Sports and Culture of Japan, 08404010.

REFERENCES

- Anders, E., & Grevesse, N. 1989, *Geochim. Cosmochim. Acta*, 53, 197
- Böhringer, H., Briel, U.G., Schwarz, R.A., Voges, W., Hartner, G., & Trümper, J. 1994, *Nature*, 368, 828
- Egger, R. J., & Aschenbach, B. 1995, *A&A*, 294, L25
- Federspiel, M., Tammann, G. A., & Sandage, A. 1998, *ApJ*, 495, 115
- Fusco-Femiano, R., et al. 1999, *ApJ*. 513, L21
- Honda, H., et al. 1996, *ApJ*, 473, L71
- Ikebe, Y. 1995, Ph. D. Thesis, University of Tokyo
- Irwin, J. A., & Sarazin, C. L. 1996, *ApJ*, 471, 683
- Ishisaki, Y. 1996, Ph. D. Thesis, University of Tokyo
- Koyama, K., Takano, S., & Tawara, Y. 1991, *Nature*, 350, 135
- Makishima, K., et al. 1996, *PASJ*, 48, 171
- Matsumoto, H., et al. 1999, *Adv. Space Res.*, in press
- Ohashi, T., et al. 1996, *PASJ*, 48, 157
- Ohashi, T., et al. 1999, *Adv. Space Res.*, in press
- Raymond, J. C., & Smith, B. W. 1977, *ApJS*, 35, 419
- Raymond, J. C. 1984, *ARA&A*, 22, 75
- Roettiger, K., Burns, J., & Loken, C. 1993, *ApJ*, 407, L53
- Sarazin, C. L., & Kempner, J. C. 1999, *ApJ*, in press (astro-ph/99 11335)
- Schindler, S., Binggeli, B., & Böhringer, H. 1999, *A&A*, 343, 420
- Shu, F. H. 1992, *The Physics of Astrophysics volume II. Gas Dynamics*, ed. D. E. Osterbrock, & J. S. Miller (University Science Books)

- Snowden, S. L., et al. 1995, *ApJ*, 454, 643
- Takizawa, M. 1999, *ApJ*, 520, 514
- Takano, S. 1990, Ph. D. Thesis, University of Tokyo
- Tanaka, Y., Inoue, H., & Holt, S. S. 1994, *PASJ*, 46, L37
- Tsusaka, Y., et al. 1995, *Appl. Opt.*, 34, 4848
- Ueda, Y., et al. 1999, *ApJ*, 518, 656
- Voges, W., et al. 1996, *Röntgenstrahlung from the Universe*, ed. H. U. Zimmermann, J. Trümper, & H. Yorke, MPE Report 263, p. 637
- Yamasaki, N. Y., et al. 1999, *Astron. Nachr.*, 320, 195

Table 1: The best-fit spectral parameters of the linking region between M87 and M49

Region	Model		Parameters			χ^2/ν
E123	single component ^a	R-S	$kT = 2.10^{+0.27}_{-0.25}$,	$Z = 0.29^{+0.32}_{-0.20}$,	$F_{X,2-10} = 1.21^{+0.16}_{-0.15}$	31.1/21
	two components ^a	R-S	$kT = 2.25^{+0.59}_{-0.29}$,	$Z = 0.2$ (fixed),	$F_{X,2-10} = 1.26^{+0.12}_{-0.15}$	27.2/20
		Brems	$kT = 0.20$ (unconstrained) , $F_{X,0.5-2} = 0.58^{+1.67}_{-0.41}$			
W123	single component ^a	R-S	$kT = 3.14^{+0.31}_{-0.34}$,	$Z = 0.63^{+0.39}_{-0.30}$,	$F_{X,2-10} = 2.04^{+0.19}_{-0.21}$	45.2/21
	two components ^a	R-S	$kT = 4.31^{+1.11}_{-0.81}$,	$Z = 0.2$ (fixed),	$F_{X,2-10} = 2.22^{+0.17}_{-0.20}$	21.8/20
		Brems	$kT = 0.32^{+0.22}_{-0.11}$, $F_{X,0.5-2} = 0.95^{+0.27}_{-0.12}$			
	single component ^b	R-S	$kT = 5.32^{+3.70}_{-1.52}$,	$Z = 0.2$ (fixed),	$F_{X,2-10} = 2.45^{+0.30}_{-0.28}$	10.5/11
	single component ^b	Power-law	$\Gamma = 1.97^{+0.28}_{-0.27}$, $F_{X,2-10} = 2.59^{+0.26}_{-0.26}$			9.9/11

^a The data in the energy range of 0.7 – 8 keV were used.

^b Only the data in the energy range 2 – 8 keV were used, and the contaminating photons outside of the region are subtracted assuming the temperature of 2 keV and metal abundance of 0.2 solar.

Note. — The kT represents temperature in keV, Z is heavy element abundance in solar unit, and Γ is photon index. The flux $F_{X,2-10}$ and $F_{X,0.5-2}$ are in 10^{-15} ergs sec⁻¹ cm⁻² arcmin⁻² in 2–10 and 0.5–2 keV range, respectively. The errors in all parameters represent 90% confidence limits. The R-S and Power-law components were modified by interstellar absorption with $N_H = 1.9 \times 10^{20}$ cm⁻².

Fig. 1.— *ASCA* observed regions superposed on the *ROSAT* PSPC contour in $0.5 - 2$ keV band. Contours show the X-Ray intensity observed by the *ROSAT* All-Sky Survey in a logarithmic scale, increasing by factors of 1.2. Red and blue circles with radii $22'$ indicate the GIS observed fields, and the red regions all containing bright sources are excluded in the present analysis. The mask regions to exclude contaminating sources are also indicated by filled green circles.

Fig. 2.— Temperature distribution of the Virgo cluster. The spectra of $0.7 - 8$ keV band were fitted with a R-S model. *left*: Temperature scale for the middle panel. *middle*: Two dimensional plot of the temperature distribution in the Virgo region. *right*: The temperature distribution as a function of distance from M87. The error bars indicate statistical errors. Triangles show temperatures at W1, W2, and W3, and rectangles are at E1, E2, and E3.

Fig. 3.— GIS spectra of W123 (red) and E123 (blue). Spectral data are shown with crosses, and the best-fit spectra of the two-component (R-S model and thermal bremsstrahlung) model are shown with solid lines. The best-fit thermal bremsstrahlung components are also indicated with dashed lines. See table 1 for the error ranges of the spectral parameters.